Biomass and Bioenergy 108 (2018) 167–177

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Research paper

How harmful is burning logging residues? Adding economics to the emission factors for Nordic tree species

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ARTICLE INFO

Keywords:
Emission factor
Logging residues
Bioenergy
Carbon
Time preference
Social cost of carbon
Picea abies
Pinus sylvestris
Betula pendula

ABSTRACT

Replacing fossil fuels by logging-residue-based bioenergy has been proposed as a way to mitigate climate change. If residues are combusted for energy, their carbon content is released immediately. Residues, that are not combusted, decompose and emit carbon gradually. The relative harmfulness of bioenergy emissions therefore depends on how strongly we prefer the slow release of carbon to an immediate one. Two factors affect this judgment: (1) our time preference and (2) our expectations regarding the relative harmfulness of future carbon emissions. Neither aspect is included in established biomass emission factors. The Effective Emission Factor (EEF), outlined in this study, includes both aspects in a transparent and tractable way. We demonstrate the concept by deriving the EEFs for the logging residues of three Nordic tree species: Norway spruce (Picea abies), Scots pine (Pinus sylvestris) and silver birch (Betula pendula). We also examine the sensitivity of the results to variation in time preference and damage expectations. The derived factors can be used to compare the harmfulness of carbon emissions from residue-based bioenergy and fossil fuel combustion and to organize bioenergy carbon taxation consistently with the taxation of fossil fuels.

1. Introduction

Logging residues from Nordic boreal forests are a renewable energy source. It has been argued that –although residue-based bioenergy is not emission free– it can help mitigate climate change, as total anthropogenic carbon emissions can be in the long run reduced by replacing fossil fuels by bioenergy [1–3]. The carbon intensity of fossil fuels is usually compared using emission factors, such as those recommended by the IPCC [4]. These factors measure immediate fuel combustion emissions. If the fuels are not combusted, no carbon is released. The same is not true for logging residues, which decompose and release carbon even if they are not utilized for energy. Constructing emission factors for residues therefore requires establishing the trade-off between current and future emissions, which is a question of economic cost-benefit analysis. This trade-off is not taken into account in pre-existing biomass emission metrics (e.g. Refs. [5,6]) apart from the Effective Emission Factor (EEF) [7].

The "harmfulness" of CO_2 emissions from residue or fossil fuel combustion can be measured in terms of social cost (i.e. the present monetary value of the social damage caused by the emissions). The EEF can be used to compare the harmfulness of fossil fuel and residue-based bioenergy emissions. As the concept is only briefly introduced in the original source [7], we discuss it here in detail. We explain its theoretical foundations and derive the EEFs for the three most common Nordic tree species. Similar factors – for any type of biomass – have not been published previously. Thus, this study serves as a proof of concept. The same idea is also applicable to residues of other tree species as well as agricultural residues. As an example of a practical application for the concept, we show how it can be used to organize the carbon taxation of logging residue-based bioenergy in a way that is consistent with fossil fuel taxation. Similar economic consistency is not attained if other pre-existing metrics are used for the same end.

1.1. Why is an economic approach needed?

Three aspects are critical in determining the trade-off between immediate emissions from residue combustion and gradual emissions from residue decomposition. The first is the emission profile (i.e. how much CO_2 is emitted, if the residues are burned, and what is the alternative time trajectory of the emissions, if the residues are left to decompose). The second is how the harmfulness of CO_2 emissions is expected to change over time (i.e. is emitting one tonne today more or less harmful than it is e.g. next year?). The third is the time preference (i.e. how strongly do we prioritize our current welfare compared to that of the future generations?). Based on these three factors, the harmfulness of emissions from residue combustion can be established and compared to

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https://doi.org/10.1016/j.biombioe.2017.11.010
Received 15 January 2016; Received in revised form 9 November 2017; Accepted 10 November 2017
Available online 21 November 2017
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fossil emissions.

A one tonne CO_2 pulse emitted today halves in the atmosphere in 45 years. A third of it remains there even after 260 years [8]. The fraction remaining in the atmosphere at any given point in time contributes to global warming, which is damaging to ecosystems and human well-being [9]. Economists measure these damages in monetary terms. The Social Cost of Carbon (SCC) is the present value of the future damages caused by the marginal tonne of CO_2, emitted at time t (see e.g. Ref. [10] or [11]). Thus, the SCC measures the harm caused by a CO_2 emission pulse (a mathematical definition for the SCC is provided in Supplement [S1]). The harm caused by burning residues is caused by advancing the timing of the emissions [7]: i.e. when the value of the damage is discounted, immediate damage is considered more harmful than gradual future damage of equal proportion.

Pre-existing biomass emission metrics are based on a different kind of thinking. The GWP_{bio} index [5] accounts for the climatic impacts as follows. Burning biomass releases carbon. The release is then compensated for by growing new biomass which gradually removes the carbon from the atmosphere (some carbon is also removed by the rest of the biosphere and the oceans). The climatic impact of a pulse emission is the time-integrated radiative forcing caused by the fraction remaining in the atmosphere until the pulse is fully compensated for. In Ref. [6] the concept is further refined to include a displacement factor [12] to account for the fossil emissions that are avoided by substituting bioenergy for fossil fuels.

Applying the GWP_{bio} index approach to the regulation of residue-based bioenergy is problematic for two reasons. First, it does not address the emissions that occur if the residues are left to decompose on site. Second, it rewards biomass user for future carbon removals which (usually) someone else will be responsible for. This has repercussions if carbon impacts throughout the economy are regulated based on a welfare-maximizing carbon pricing policy [7] or [13,14]. Under such a policy, all emissions and removals are equally priced according to the SCC [13]. Removals by growing biomass are subsidized [7,15], while emissions from combustion and decay are taxed [7]. These incentives encourage landowners and consumers to increase removals and reduce emissions by adjusting forest management and biomass use. However, if the reward for future removals is in advance given to someone else than the landowner, her incentives are distorted and the policy does not guide her behavior correctly. Thus, the landowner – rather than the consumer – should be rewarded for the removals. Similarly, for consistency, a displacement factor should not be used to reward the biomass user for avoided fossil emissions [7]. If fossil emissions are taxed, the reward for avoided fossil emissions –i.e. avoided taxes– is already given to the consumer who reduces fossil fuel consumption. Rewarding the biomass user for the same reductions amounts to double-counting.

The climatic impacts of Nordic residue-based bioenergy have been studied by Repo et al. [2,16,17], using life-cycle assessments (LCA) methods. Similar studies conducted elsewhere are reviewed in Ref. [18]. Our method, based on cost-benefit analysis, differs from this approach in two ways: (1) we account for the changing SCC over time, and (2) we include an explicit time preference rate.

The radiative forcing caused by incremental CO_2 emissions (slightly) decreases as the atmospheric carbon concentration increases [19]. Thus, a CO_2 tonne emitted in the future warms the atmosphere less than one emitted today. The impact of the changing atmospheric mixing ratios on radiative forcing is taken into account in appropriately conducted LCAs [20], such as [2]. However, measuring radiative forcing alone is not enough to capture the harmfulness of emissions. Radiative forcing causes warming which causes social damage. Thus, the harmfulness of an emission pulse depends on (i) the temporal radiative forcing profile of the pulse, and (ii) development of the social cost of (i.e. the value of the damage caused by) marginal radiative forcing over time [21]. The latter is expected to increase over time as climate change proceeds and the global economy grows [21–24]. This impact is not captured by purely physical metrics based on radiative forcing, such as Global Warming Potential (GWP) [25]. GWP is commonly applied in LCA for making comparisons between greenhouse gasses and over time [20]. The Absolute Global Warming Potential (AGWP) of a gas is the time-integrated radiative forcing caused by an emitted tonne over a given timespan (usually 100 years). The GWP of the gas is the ratio of its AGWP to that of CO_2. Thus, because AGWP and GWP are pure 'forcing metrics', they do not sufficiently measure the harmfulness of emissions [26,27]. Other alternative climate metrics are reviewed in Refs. [29,30].

The fact that radiative forcing can be measured more accurately than climate damage may explain why 'forcing metrics' are preferred to 'damage metrics' in LCA. Forcing estimates are somewhat uncertain [29], but damage estimates are even more so, as they contain the uncertainty of the forcing caused by the emissions as well as that of the damage caused by the forcing [21]. However, the results of LCA studies are used to inform policy about the relative harmfulness (or harmlessness) of using alternative feedstocks. If climate policy is e.g. based on the principle of welfare maximization (i.e. maximizing the difference between social benefits and costs), the monetary value of damage is a more relevant variable than forcing. By conducting our analysis using a damage metric we therefore aim at regulating the accurate policy target (damage) at a low precision, rather than an inaccurate target (forcing) at a higher precision.

Time preference is the second major difference between cost benefit analysis and LCA. In economics, the discount rate indicates time preference. A positive discount rate implies that the costs and benefits (of e.g. reducing emissions), incurred tomorrow, are given less weight than those incurred today (higher the rate, the smaller the weight). In LCA, on the contrary, there is (usually) no explicit time preference [20]. All emissions are weighted equally regardless of their timing, which is the same as applying a zero discount rate. However, there is a 'hidden time preference' that depends on the choice of time horizon of the emission metric (e.g. GWP_{100} gives equal weight to all radiative forcing incurred during the first hundred years, but zero weight to that incurred thereafter). Thus, applying a short (long) time horizon emphasizes immediate (gradual) climatic impacts. Also an explicit time preference can be included in LCA [28] but, so far, it has not become a common practice.

The question of time preference is central to establishing what weight we give to reducing net emissions today vs. reducing them in the future. There is no 'objectively correct' time preference. Likewise, no-one can exactly foretell the future development of the SCC. However, despite these uncertainties, 'time preference' and 'damage expectations' are crucial variables that cannot be disregarded without losing policy-relevance [26]. We show how these variables can be taken into account in a transparent and tractable manner.

2. Materials and methods

2.1. Social cost of carbon as a measure of damage

The SCC at any given point in time depends on the expected future damages and the rate at which they are discounted. The appraisal of global damages that occur in the future is naturally subject to large uncertainties. Damage estimates vary considerably [24,31]. Likewise, economists' views regarding the rate at which environmental costs and benefits should be discounted vary (see e.g. Stern vs. Nordhaus [32,33]). Nevertheless, most economists tend to recommend the use of relatively low, positive discount rates [34].

SCC time paths are usually projected using integrated assessment models, e.g. Refs. [22,35,36]. One meta-analysis of these projections suggests that, on average, the SCC estimates rise at an annual rate of 2% [24]. The Interagency Working Group (IWG) in the United States (under the Obama administration) produced SCC guideline values [37] that can be applied in public policy related cost-benefit analyses (see Ref. [10] for discussion). The guideline values for 3% and 5% discount

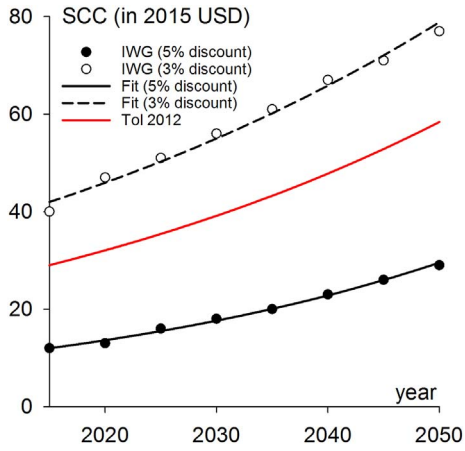

Fig. 1. Projected Social Cost of Carbon 2015-2050. The round symbols indicate reported Interagency Working Group (IWG) SCC values at 3% and 5% discount rates [36]. The black lines are exponential fits of the form $SCC = p_0 e^{g(year-2015)}$. At a 3% discount rate, p_0 = \$41.99 and g = 0.0188. At a 5% discount rate, p_0 = \$11.967 and g = 0.0258. The red line is the average expected SCC time path based on a meta-analysis of economic literature [23], for which p_0 = \$29 and g = 0.02 (the applied discount rate declines over time). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rates are shown in Fig. 1. The presented values exemplify SCC trajectories that a regulator might realistically consider when valuing the future carbon impacts of proposed policies (we use US government values as the EU has not issued similar guidelines). In general, lower discount rates are associated with higher SCC values (as the future damages receive more weight) and lower SCC growth rates. In the IWG report, the growth rate of SCC is always lower than the discount rate.

For convenience, we hereafter refer to the SCC as the carbon price. The carbon price trajectory $p(t)$ is a function of time t, and is measured in € tCO_2^{-1}. We approximate the trajectory by an exponential function,

$$p(t) = p_0 e^{gt}, \tag{1}$$

where p_0 is the initial price and, g, is its temporal growth rate. This simple formulation can be flexibly calibrated to depict a set of alternative carbon price trajectories (Fig. 1).

2.2. Relative emission factor

The social cost of releasing a unit of carbon, i.e. the SCC, at time t is $p(t)$. It is the same for residues and fossil fuels. However, the two energy sources differ in terms of what happens to the carbon content of the fuels, if it is not released through combustion. Unless combusted, fossil carbon stays stored in the ground and no carbon is released. The same is not true for carbon in logging residues. Given that a stand has been logged and residues have been generated, the carbon contained within the residues will be released through decomposition unless they are collected for combustion. This unavoidable gradual carbon release reduces the net social costs of residue combustion emissions.

There are several types of logging residues (e.g. foliage, branches and stumps). The residues' decay rates depend on their size (diameter) and chemical composition [38]. Let i and t denote the residue type and the calendar time of the harvest, respectively. The function $d_i(t, s)$ expresses the fraction of a unit of carbon initially contained in harvesting residues remaining in the ecosystem $s \geq 0$ years after the harvest. As decay rates are affected by the climate, and the climate is expected to change over time, the fraction of the carbon remaining in the ecosystem s years after the harvest also depends on t. The function $m_i(t, s)$ indicates the carbon release (i.e. decomposition emissions) at time s, as a share of the initial carbon input, i.e.

$$m_i(t, s) := -\frac{\partial d_i(t, s)}{\partial s}. \tag{2}$$

The unit of m_i is yr^{-1}. There is a minus sign on the right-hand side in (2), as the change in the carbon stock is negative. In what follows, we assume that all carbon that is released is released as CO_2 (i.e. released carbon is converted to CO_2 by the factor $\rho \approx 3.67$ tCO_2 tC^{-1}). We extend the formulation to the multi-GHG case in the appendix.

The social cost (€ tCO_2^{-1}) c_i, of releasing 1 tC by burning type i residues is

$$c_i(t) := \rho p(t) - \rho \int_0^{\infty} e^{-rs} p(t+s) m_i(t, s) ds, \tag{3}$$

where r is the discount rate [7]. The first term on the right, $\rho p(t)$, is the social cost of releasing a tonne of carbon into the atmosphere through combustion. The second term is the social benefit of the avoided emissions from the decaying residues. The projected CO_2 emissions from decomposition emissions, $\rho m_i(t, s)$, are valued according to future carbon prices, $p(t + s)$, and then discounted to present value, e^{-rs}. Because residues decay, $c_i(t) < \rho p(t)$.

Following [7], we define the relative emission factor (REF) ε_i,

$$\varepsilon_i(t) := \frac{c_i(t)}{\rho p(t)}. \tag{4}$$

The REF is a dimensionless coefficient which expresses the relative harm caused by releasing a unit of carbon immediately through combustion instead of letting it be released gradually through decay. Substituting (1) and (3) into (4) and simplifying, we obtain

$$\varepsilon_i(t) = 1 - \int_0^{\infty} m_i(t, s) e^{-ns} ds, \tag{5}$$

where $n = r - g$ is a "net discount rate", which accounts for the time preference (indicated by r) and expectations regarding the increase in the carbon price (indicated by g). If $n = 0$, equal importance is assigned to current and future emissions, in which case $\varepsilon_i(t) = 0$, if all carbon is eventually released. If $n > 0$, today's emissions are given a greater weight than future ones (the higher the net discount rate the stronger the relative emphasis on immediate impacts). For example, in the US government SCC projection relying on a 5% real interest rate (Fig. 1), $n = 5\% - 2.58\% = 2.42\%$, and with 3% interest rate, $n = 3\% - 1.88\% = 1.12\%$. Thus, g decreases with r in such a way that also n decreases with r.

The REF receives values between 0 and 1 when $n \geq 0$. The REF of a fuel whose carbon content would be released immediately anyway is 0. The REF of all fossil fuels is 1 (as there carbon content would not otherwise be released). Notably, as the REF is the ratio of the social cost of emitting carbon by burning residues to that of emitting the same amount of carbon by burning fossil fuels, it is the economically consistent equivalent of the GWP_{bio} factor [5,6], which is the ratio of the AGWP of biomass carbon emissions to that of fossil carbon emissions.

2.3. Effective emission factor

Emission factors are used for comparing the carbon intensity of energy production using different fuels. For example, the emission factors for natural gas and coal are 55 and 93 gCO_2 MJ^{-1}, respectively [39]. Hence, we can infer that gas is cleaner than coal. The Effective Emission Factor (EEF) enables similar comparisons between residue-based bioenergy and fossil fuels in terms of the relative harmfulness of the emissions [7].

The nominal emission factor, γ_i (gCO_2 MJ^{-1}), indicates how much CO_2 is emitted when a fuel is combusted to release 1 MJ of energy. It depends on the fuel's carbon density, κ_i (gC kg^{-1}), and its net calorific value, η_i (MJ kg^{-1}). The inverse of η_i expresses how much fuel in kilograms is needed to release a MJ of energy. As earlier, carbon mass is scaled to CO_2 by the factor ρ. The nominal emission factor is the

product of these three components:

$$\gamma_i = \eta_i^{-1}\kappa_i\rho. \quad (6)$$

The EEF $\hat{\varepsilon}_i(t)$, is obtained by multiplying the nominal emission factor, γ_i, by the REF, which adjusts the actual CO_2 emissions to account for their relative harmfulness, i.e.

$$\hat{\varepsilon}_i(t) := \gamma_i\varepsilon_i(t). \quad (7)$$

As $\varepsilon_i(t) = 1$ for fossil fuels, their EEFs are the same as their nominal emission factors. However, for logging residues, $\varepsilon_i(t) < 1$ and, thus, $\hat{\varepsilon}_i(t) < \gamma_i$.

2.4. Numerical methods

The REFs and the EEFs were calculated for three species and five residue types at two sites. The three species are Norway spruce, Scots pine and silver birch. Together they make up over 95% of the growing stock in Finnish forests [40]. The five residue types (by diameter) are: foliage (0.1 cm), small branches (1 cm), large branches (5 cm), small stems removed by thinning (10 cm) and stumps (30 cm). The two sites are Sodankylä and Hämeenlinna, which depict climatic conditions in the Northern and Southern Finland respectively. The decomposition of residues at both sites was considered in three alternative climate scenarios: constant climate, weak climate change and strong climate change.

The REFs were calculated according to Equation (5) and converted to EEFs according to Equation (7). However, the infinite time horizon is approximated by a 300 year period. (Within that time most of the residues left on site have decomposed. The error resulting from the use of a 300 year time horizon instead of an infinite one is largest when the applied net discount rates are close to zero. The errors diminish as the discount rate increases.). To account for a wide range of potential combinations of interest rate r and SCC growth rate g, the analysis was conducted with net discount rates in the range 0–10%.

The direct emissions from burning residues were calculated based on the net calorific value and carbon content of logging residues, obtained from Refs. [41,42]. The carbon content of stumps was assumed to be the same as the carbon content of stems. The emissions from fossil fuel and residue combustion were calculated according to Equation (6). The parameter values are summarized in Table 1. The emissions factors of fossil fuels are the official values used by the government of Finland [39] and are in line with the IPCC Guidelines for National Greenhouse Gas Inventories [4].

The decomposition of logging residues was simulated using the soil carbon model Yasso07 [38,43], which has also been utilized in previous studies considering the climatic impacts of Nordic logging residues [2,16,17]. In Yasso07, biomass decomposition depends on litter size, the chemical composition of the litter, and the climate. The parameter values describing the chemical composition the residues are given in the supplement (S2). The values were adopted from Ref. [2], where the parameter set is assembled from various sources. As the variation in the composition of residues affects decay, the average decomposition time path was determined using a sample of 30 model runs for each residue type.

The climate data for the Normal Period 1981-2010 were obtained from the Finnish Meteorological Institute [44]. These data depict the past climate. The climate is expected to change during the next century. As the magnitude of the change is uncertain, the IPCC uses Representative Concentration Pathways (RCPs) to probe alternative climate trajectories. The RCPs are named after their peak radiative forcing (e.g. in RCP26 radiative forcing peaks at roughly 2.6 Wm^{-2}). RCPs 2.6 and 8.5 are the two extremes. The former depicts modest global warming, while the latter depicts strong warming. Multimodel projections based on RCP26 [45], suggest a 2 °C rise in the mean annual temperature over the next century throughout Finland and an 5% increase in precipitation. Corresponding projections based on RCP85 suggest a 6 °C temperature rise and 15% and 25% increases in precipitation in the south and north, respectively. The amplitude of the annual temperature variation is expected to decrease [46].

To account for the climatic uncertainty, we conducted our calculations using three climate scenarios: constant climate (CC), modest climate change (RCP26) and strong climate change (RCP85). In the two latter scenarios, climate change was assumed to occur during the first century, after which the climate was assumed to stabilize. Temperatures and precipitation for the first century were interpolated linearly. The increase in temperature amplitude was approximated based on the change in the temperature difference between the coldest and the warmest day of the year in RCP85 [45]. The change in temperature amplitude in RCP26 was assumed to be a third of the respective change in RCP85 (proportional to the temperature change). The parameter values in the scenarios are given in Table 2.

Table 1
Immediate CO_2 emissions from biomass and fossil fuel combustion.

Fuel		Net calorific value	Mass C content	CO_2 emissions	CO_2 emissions
		MJ kg^{-1}	(%)	g MJ^{-1} (γ)	tons MWh^{-1}
Spruce	Foliage	19.19	51.30	98	0.350
	Branches	19.36	53.36	101	0.361
	Small stems	19.05	52.43	101	0.360
	Stumps	19.18	52.43	100	0.358
Pine	Foliage	21.04	52.20	91	0.325
	Branches	20.01	53.53	98	0.350
	Small stems	19.31	52.34	99	0.350
	Stumps	22.36	52.34	86	0.307
Birch	Foliage	19.61	48.68	91	0.325
	Branches	18.53	48.67	96	0.344
	Small stems	18.61	47.43	93	0.334
	Stumps	18.50	47.43	94	0.336
Natural gas				55	0.198
Coal				93	0.336
Peat				106	0.381

3. Results

3.1. Decay and emissions

The climate in the south is warmer and wetter than in the north. Hence, residues decay faster in the south. Small residues decay faster than large ones. In Fig. 2, we illustrate the impact of climate and litter size on the decomposition of logging residues using spruce branches and stumps as examples. Although the climate affects decay, gradual climate change has only a slight impact on the decomposition of logging residues generated today. The effect on small rapidly decomposing

Table 2
Climatic parameters [43–45].

Climatic parameters	Hämeenlinna				Sodankylä			
	2015	2115	2115	2115	2015	2115	2115	2115
	CC	CC	RCP26	RCP85	CC	CC	RCP26	RCP85
Mean annual temperature (°C)	4.5	4.5	6.5	10.5	−0.5	−0.5	1.5	5.5
Temperature amplitude[a] (°C)	11.9	11.9	11.1	9.7	14.0	14.0	13.2	11.7
Precipitation (mm)	615	615	646	707	521	521	547	651

[a] Half the difference between the mean temperature of the warmest and coldest month.

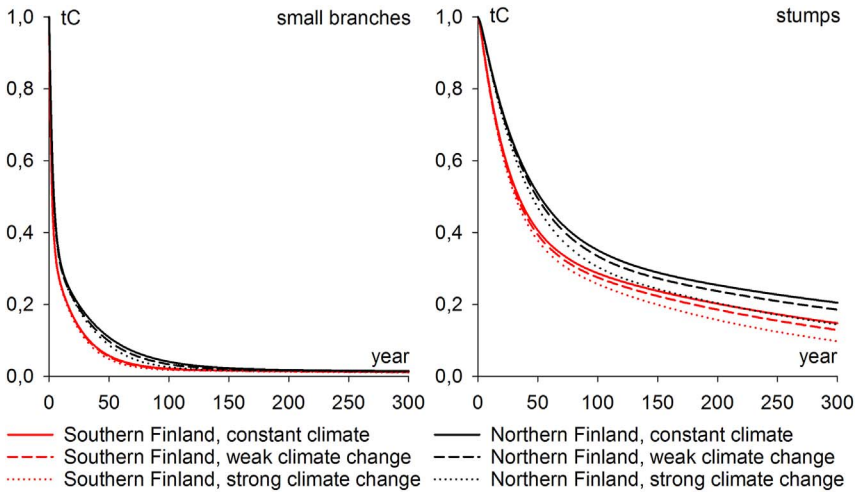

Fig. 2. Decomposition of spruce branches and stumps with an initial carbon content of 1 tC. Carbon remaining in the ecosystem *x* years. Mean of 30 simulations.

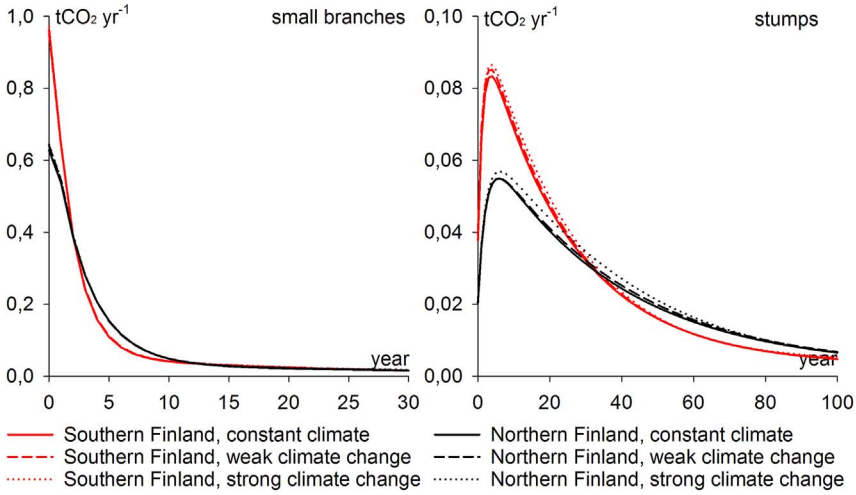

Fig. 3. CO_2 emissions from decomposing spruce branches and stumps, with an initial carbon content of 1 ton of C (corresponding to 3.67 tons of CO_2). Mean of 30 simulations.

residues, such as small branches, is almost negligible. The effect on large slowly decomposing residues, such as stumps, is larger. The decomposition CO_2 emissions are shown in Fig. 3.

The progress of the decomposition and the timing of the emissions depend on the initial chemical composition of the residues which varies naturally between observations. Figs. 2 and 3 show the means of a sample of 30 model runs. The variation in the decay of spruce residues is illustrated in the supplement (S3).

3.2. Relative emission factors

The REFs by species, residue type and location are shown in Fig. 4. At low net discount rates the REFs of all residues are low. Zero is the lowest net discount rate, n, applied in the analysis. When $n = 0$, the present value of the social cost of emissions in all time periods is equal: future emissions from decomposing residues are considered as harmful as carbon emissions from fuel combustion in this period (see Equation (5)). Therefore, the opportunity cost of burning the residues is low, as most of the carbon in them would be released anyway during the first 300 hundred years of decomposition (i.e. the time horizon used in the calculations). Thus, when $n = 0$, the REF is solely determined by the amount of carbon remaining in the soil at the end of the time horizon. As the length of the time horizon approaches infinity, the zero-net-discount-rate REFs of all residues approach zero. Generally, the REFs increase with the net discount rate, as the benefit of avoiding decomposition emissions in the future is valued less. The REFs of large residues increase more rapidly than those of small residues.

Small residues have lower REFs than large residues, as they decay and emit carbon faster than large ones (Figs. 2 and 4). The opportunity cost of burning small residues is lower than that of large residues. Likewise, as residues decay faster in the warm south than in the cold north (Fig. 2), the REFs for all residues are systematically lower in the south (Fig. 4).

The impact of climate change on the REFs depends on the applied net discount rate. At low net discount rates the REFs vary considerably, in relative terms, depending on which climate scenario is chosen (Fig. 4). For example, at a 0% net discount rate, the REF for spruce stumps in Southern Finland is 0.148 in constant climate and 0.098 with strong climate change. The difference is -33.9% . The REFs of large residues depend more strongly on the choice of climate scenario than the REFs of small residues. For example, at a 0% net discount rate, the REF for small spruce branches in Southern Finland is 0.126 in constant climate and 0.104 with strong climate change. The difference is -17.5%, which is less than in the case of stumps. The role of the choice of climate scenario is reduced as the net discount rate increases. Already at a 2% net discount rate the difference in the REFs for spruce stumps in constant climate and with strong climate change is reduced to -4.0%. Increasing the net discount rate increases the relative weight assigned to ‘near future decomposition emissions’ compared to ‘distant future decomposition emissions’. As gradual climate change only slightly affects ‘near future decomposition emissions’ (even if the long-term climate change trend is strong), higher net discount rates reduce the role of climate expectations in determining the REF.

The REFs in Fig. 4 are means of a sample of 30 simulations. The

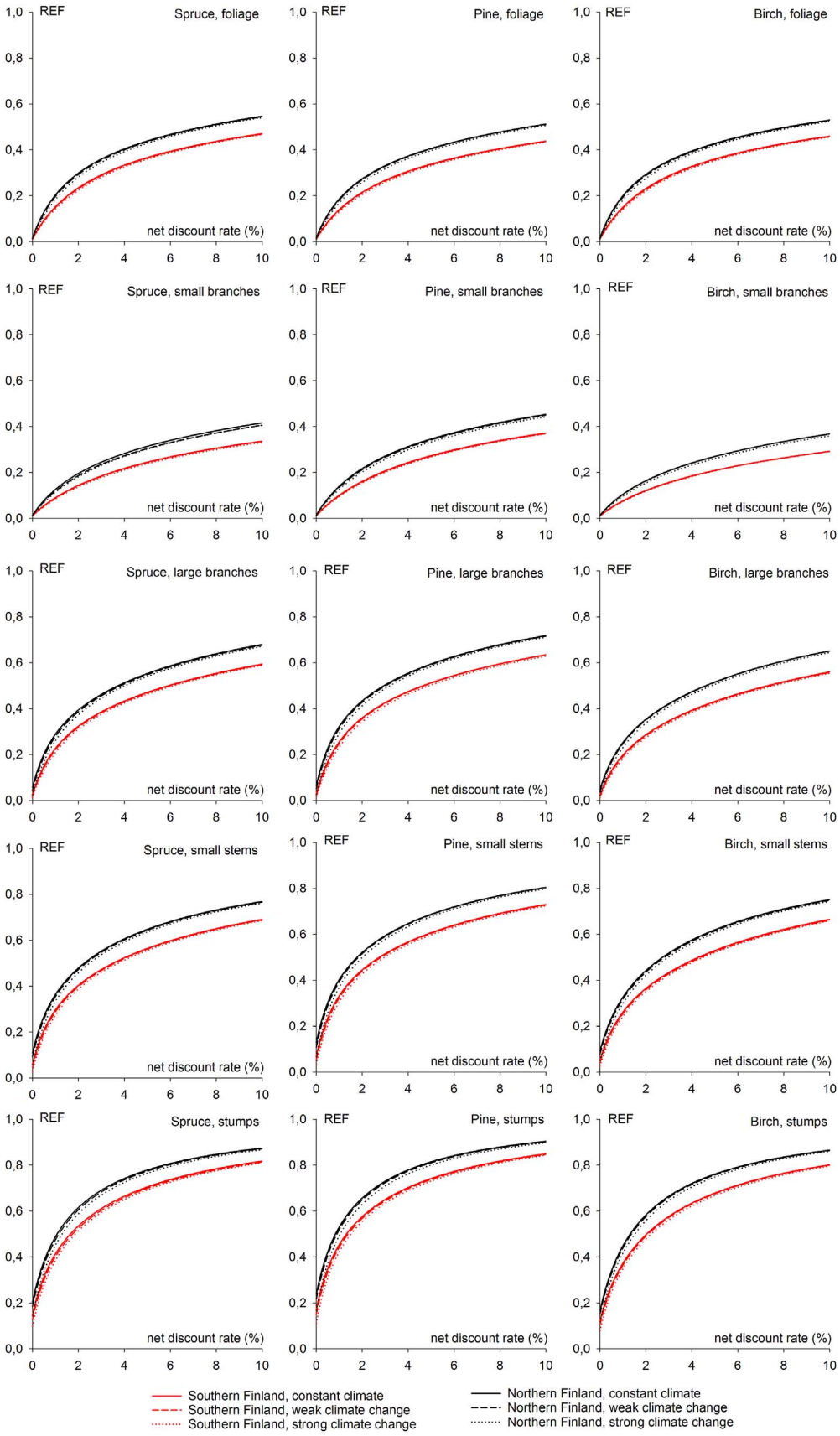

Fig. 4. Relative emission factors (REFs) for spruce, pine and birch logging residues. Mean of 30 simulations.

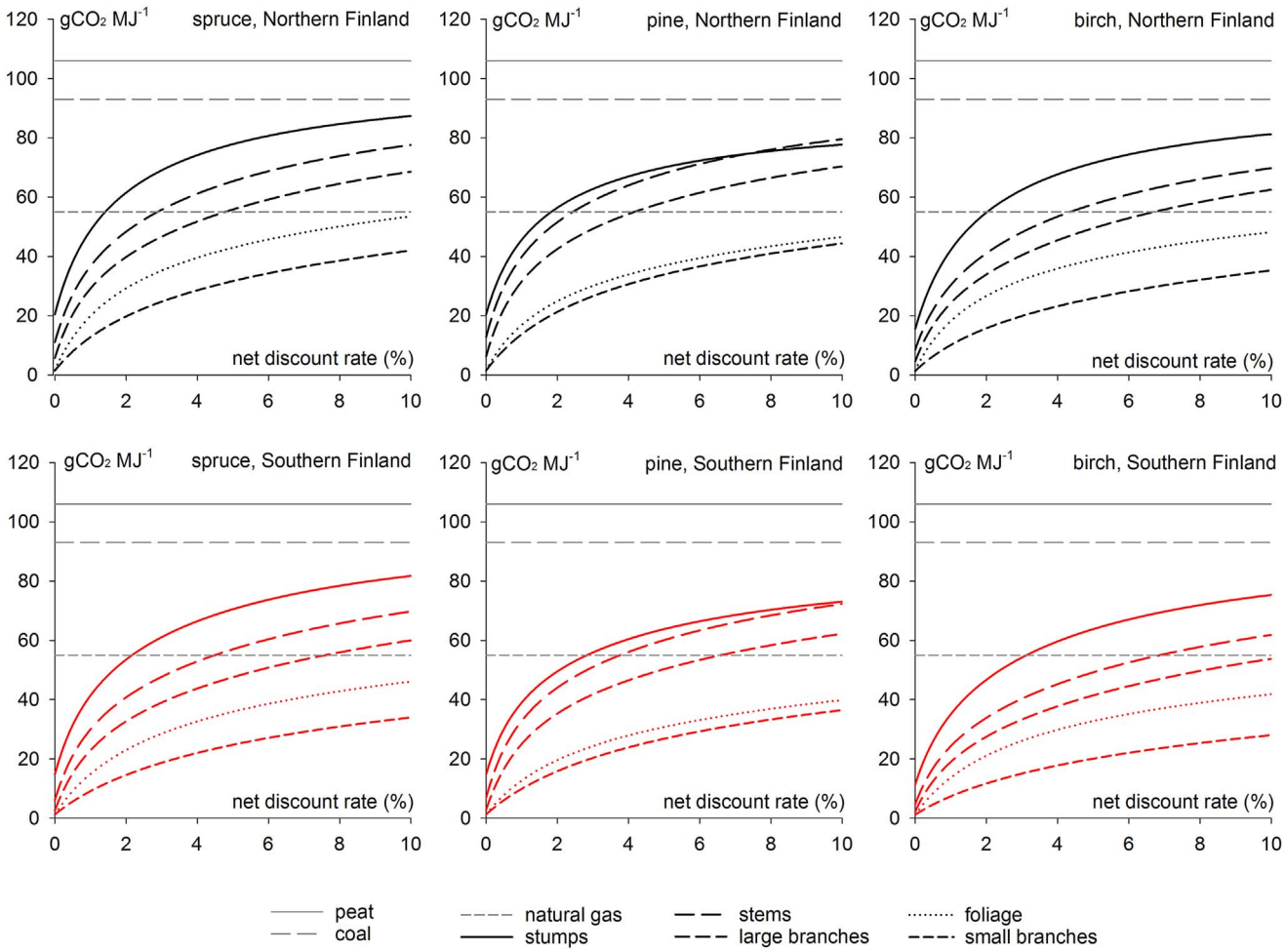

Fig. 5. Effective emission factors ($gCO_2\ MJ^{-1}$) for spruce, pine and birch in constant climate compared to the emissions factors of fossil alternatives.

variation in the REFs of individual observations, due to natural variation in the chemical composition of the residues, is relatively small. A detailed account of the variation is provided in the supplement (S4). At net discount rates above 2%, 95% of the observations for all residues except small branches fell within a range of ± 1% to ± 2. 5% of the sample mean. For small branches, the corresponding range was roughly ± 8% to ± 15% depending on species and climate scenario.

3.3. Effective emission factors

To illustrate the EEF concept it suffices to consider only one climate scenario (constant climate). In the above, we have shown that when the net discount rate is sufficiently large (e.g. > 2%), the choice of climate scenario only slightly affects the REFs (Fig. 4) and, hence, the EEFs which are linear transformations of the REFs (Equation (7)). As the REFs for residues are slightly higher in a constant climate than in a changing one, the constant climate assumption slightly exaggerates the EEFs in a changing climate. The EEFs by species, residue type and location are shown in Fig. 5.

In all circumstances, small branches have the lowest EEF. It is even lower than that of foliage, which decomposes slower due to its chemical composition. Birch branches have a lower EEF than spruce and pine branches. Stumps always have the highest EEF, except in one case: at very high net discount rates, the EEF of pine stems in the north is higher than that of stumps. Generally, pine stumps have a lower EEF than birch and spruce stumps. The low EEF of pine stumps can be attributed to their high net calorific value (Table 1). The calorific value is associated with the concentrations of extractives, which vary between stumps. Using a lower value (such as the value reported in Ref. [47]) would imply a higher EEF.

4. Discussion

4.1. How harmful is burning residues for energy?

The relative harmfulness of burning residues for energy depends on our SCC expectations and our choice of discount rate, which reflects our time preference (Fig. 5). When 2160 economists were asked to identify an appropriate discount rate for discounting environmental costs and benefits, most respondents gave an answer in the 1–6% range [34]. Using this sample as a guideline, we interpret Fig. 5 by focusing on this range of net discount rates. Notably, as we use net discount rates ($n = r - g$) instead of real interest rates (r), our analysis covers real interest rates even beyond 10% whenever the SCC growth rate $g > 0$. Generally, applying a low (high) discount rate emphasizes long-run (short-run) impacts –much like applying a long (short) time-horizon in the measurement of cumulative emissions.

When $n < 6\%$, burning logging residues is always less harmful than using coal or peat (in terms of climate impacts). At low net discount rates (i.e. roughly $n \lesssim 1.5\%$) all residues are always a climate-friendlier option than natural gas, which is the cleanest fossil alternative. However, at slightly higher net discount rates, natural gas is less harmful than burning large residues (i.e. stumps, stems and large branches in the north; stumps and stems in the south). Nevertheless, foliage and small branches are always less harmful than natural gas. Low discount rates imply high SCC values [10] but also relatively low

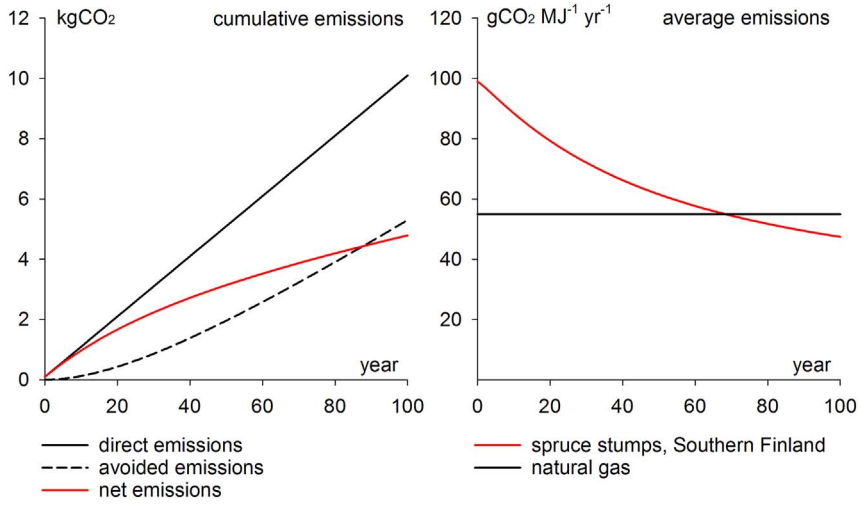

Fig. 6. Cumulative net emissions and average annual emissions from the energy use of spruce stumps in Southern Finland in constant climate. Net emissions are direct emissions minus avoided emissions. Average annual emissions are cumulative net emissions divided by the time elapsed since start of the stump-burning practice. The approach is adapted from Repo et al. [2]. The data is from this study. For simplicity, the repayment time is illustrated in terms of carbon emissions (instead of the radiative forcing) and without production chain emissions.

EEFs for all residues. This suggests that a strict climate policy might not necessarily rule out the utilization of slowly decaying residues.

The US Government SCC guideline values (Fig. 1) serve as another point of reference, as they depict the kind of assumptions a regulator might realistically make about r and g. Assuming that $r = 3\%$, $g = 1.88\%$ and, thus, $n = 1.12\%$, burning residues is always less harmful than the use of fossil fuels. However, given that $r = 5\%$, $g = 2.58\%$ and, thus, $n = 2.42\%$, the situation is more nuanced. In the south, burning all residues apart from spruce and pine stumps is less harmful than using natural gas. In the north, stumps of all varieties as well as small pine stems are considered dirtier than natural gas. Nevertheless, all residue types are always less harmful than peat and coal.

4.2. Comparison with an earlier studies

The climatic impacts of Nordic logging-residue-based bioenergy have been previously assessed by considering the carbon debt repayment time of bioenergy [2,16]. Switching from fossil fuels to bioenergy generates a carbon debt, which is then gradually repaid as the cumulative emissions from the bioenergy production system stabilize, whereas fossil emissions would not [1,48]. The concept is illustrated in Fig. 6. Assume that 1 MJ of energy is released by burning spruce stumps. Burning the stumps releases CO_2 immediately (direct emissions in Fig. 6). However, removing the stumps from the forest reduces the emissions from natural decomposition (avoided emissions in Fig. 6). The alternative to burning stumps is using natural gas. Releasing 1 MJ of energy from natural gas causes 55 g of CO_2 emissions (right panel in Fig. 6). If we start burning stumps and natural gas today, releasing 1 MJ of energy from both every year, it will take 70 years until the cumulative emissions from natural gas use overtake the cumulative net emissions from stump burning. In the right panel of Fig. 6, the same idea is expressed in terms of average annual emissions.

The term ‘repayment time’ refers to the time it takes for residue based bioenergy to become cumulatively less emission intensive than a given fossil alternative. To compare our results with [2], we calculated the repayment times for spruce residues using natural gas as reference fossil alternative. The comparison between EEFs (at a net discount rate of 3%) and repayment times is shown in Fig. 7. The two variables are highly correlated. Thus, our results confirm the findings of Repo et al. [2] regarding the ranking of different residue types' climatic impacts; both metrics e.g. suggest that burning branches is less harmful than burning stumps.

4.3. Taxation of residue-based bioenergy

A well-known economic principle is that the socially optimal tax on a negative externality, such as CO_2 emissions, should equal the social value of the damage [49]. Thus, the optimal tax on fossil CO_2 emissions is equal to the social cost of carbon, i.e. $p(t)$. Following the same principle, the optimal emission tax (€ tCO_2^{-1}) burning residues can be determined based on their REF and the carbon price [7]. It is $\tau_i = \varepsilon_i(t)\, p(t)$. Alternatively, the tax can be based on the carbon content (€ tC^{-1}). In that case, $\tau_i = \varepsilon_i(t)\rho\, p(t)$. The emission tax per energy unit (€ MJ^{-1}) is obtained by multiplying the EEF by the carbon price, i.e. $\hat{\tau}_i = \hat{\varepsilon}_i(t)\, p(t)$.

In Table 3 we illustrate bioenergy taxation based on REFs and EEFs, using spruce residues in Southern Finland as an example. The taxes are expressed relative to two “reference prices” for carbon prices. The first reference is the EU ETS carbon price (roughly 8 € tCO_2^{-1} in the autumn of 2015). The second reference is the carbon dioxide tax on heat and power plant fossil fuels in Finland (45 € tCO_2^{-1} in 2015). In the examples we assume a 2.42% net discount rate (i.e. $r = 5\%$, $g = 2.58\%$ as in Fig. 1). The emission taxes per energy unit are scaled to € GJ^{-1} and € MWh^{-1}.

Ideally (if the regulator wishes to implement a cost-effective welfare-maximizing climate policy), the above-described bioenergy taxation should be implemented as a part of a comprehensive scheme in which all land use sector carbon fluxes are priced consistently with fossil emissions [14]. In such a system, carbon removals by vegetation are subsidized and all emissions from combustion and decomposition are taxed. The taxation can be organized in various ways. The bioenergy taxes presented in Table 3 are compatible with a system, in which a landowner is taxed for future emissions from decaying residues in a single installment when the residues are generated (based on their decay profile, the carbon price and a given net discount rate) [14]. In some parts of the world it is common to burn residues, i.e. slash, in piles. Under comprehensive land use sector carbon taxation, emissions from pile burning are taxed in the same way as bioenergy emissions. The same emission factors can be used to determine the taxes for both practices.

A comprehensive climate policy to regulate all emissions in an economy [7,14] would incentivize changes in stand-level forest management through mechanisms such as forest carbon pricing and bioenergy taxation (which affects the price at which landowners can sell residues). Changes in forest management imply changes in carbon storage. The social value of these carbon impacts is not included in taxes based on REFs and EEFs, as including them would be double-counting. Under comprehensive carbon pricing, the reward for storing carbon by altering forest management is generated through the interplay of distinct incentives, i.e. subsidies for removals and taxes on emissions. Together these incentives encourage increasing and prolonging carbon storage. The changes in forest management cannot

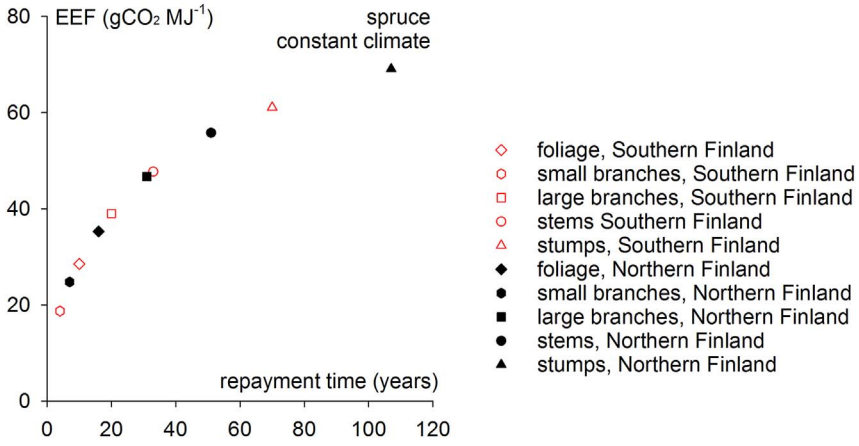

Fig. 7. Effective emission factor and natural gas repayment time for spruce residues. The EEF is calculated assuming a 3% net discount rate and constant climate. 'Repayment time' refers to the time it takes for residue based bioenergy to become cumulatively less emission intensive than natural gas.

Table 3
Example of the carbon taxation of residue-based bioenergy. Assumptions: spruce residues, Southern Finland, constant climate, $n = 2.42\%$.

		Foliage	Small branches	Large branches	Small stems	Stumps
8€ carbon price						
Emission tax	€ tCO_2^{-1} (€ tC^{-1})	2.09 (7.65)	1.30 (4.78)	2.82 (10.35)	3.48 (12.79)	4.56 (16.75)
Emission tax per energy unit	€ GJ^{-1} (€ MWh^{-1})	0.20 (0.73)	0.13 (0.47)	0.28 (1.02)	0.35 (1.25)	0.46 (1.63)
45€ carbon price						
Emission tax	€ tCO_2^{-1} (€ tC^{-1})	11.73 (43.05)	7.32 (26.88)	15.86 (58.22)	19.60 (71.92)	25.67 (94.21)
Emission tax per energy unit	€ GJ^{-1} (€ MWh^{-1})	1.15 (4.11)	0.74 (2.64)	1.60 (5.73)	1.98 (7.06)	2.57 (9.19)

be attributed to any single component of the regulatory system alone (e.g. bioenergy taxation).

4.4. Limitations of the approach

The applied approach has two limitations. First, the EEF is a measure based on climatic damage. It is not a measure of overall ecological impacts. In addition to influencing the climate, residue collection removes nutrients from the ecosystem [50] and may affect biodiversity [51]. Taking these impacts into account is important when deciding whether or not to collect the residues. However, they are not included in the EEF as they do not directly affect the climate.

Second, in our calculations we assume that all carbon is released as CO_2. However, some of it may be released as other GHGs during combustion or decay (especially CH_4, see e.g. Ref. [52]). In the appendix we expand the EEF to cover these releases. Other GHGs are not included in the numerical results presented in Section 3, as our soil model only keeps track of soil carbon stocks and does not identify specific GHG fluxes. Refining the estimates to account for CH_4 fluxes is left to further research. The presented REF and EEF estimates are therefore most reliable for residues obtained from relatively dry and aerobic conditions, where only little carbon is released as methane.

5. Conclusion

The EEF enables comparing the harmfulness bioenergy and fossil fuel emissions, taking into account the regulator's time preference and damage expectations. Although individual preferences and expectations differ, three general conclusions hold when the parameters' values are within the scope of common expert opinion: (1) in terms of climatic impacts, bioenergy of Nordic forest residues is preferred to peat and coal, and (2) small branches and foliage are preferred to natural gas, which is the cleanest fossil alternative. However, (3) comparisons between large residues (large branches, small stems and stumps) and natural gas are sensitive to the assumptions. Whatever the regulator's time preference and damage expectations are, the EEF enables organizing the taxation of residue-based bioenergy consistently with fossil fuel taxation.

Acknowledgements

The research was conducted in the Academy of Finland projects Green Economy and Policies (grant no. 257919) and OPTICA (grant no. 295870). We thank Jani Laturi and two anonymous reviewers for their helpful comments. We wish to convey our special thanks to the reviewer whose comments led us to consider the multi-gas case presented in the Appendix.

Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2017.11.010.

Appendix

In the main text we assume that all carbon contained in the residues is released as CO_2. Here, we show how the EEF can be extended if some of the carbon is released as other GHGs besides CO_2 during combustion or decay.

Different GHGs (e.g. CO, CO_2 or CH_4) are distinguished by the index $j \in J$. The parameter λ_{ij} is the share of carbon contained in the residues of type i released as a given GHG during combustion. The function $\phi_{ij}(t, s)$ indicates the share of carbon released as a specific GHG at each point of the decomposition process. λ_{ij} and $\phi_{ij}(t, s)$ are unitless, and $\sum_j \lambda_{ij} = 1$ and $\sum_j \phi_{ij}(t, s) = 1$, for all i, t and s. The parameter ρ_j ($t_j\ tC^{-1}$) scales carbon mass to

the mass of a GHG of type j. The (shadow) price of each GHG is p_j (€ t_j^{-1}). The derivation of economically consistent shadow prices for GHGs is briefly discussed in supplement (S1). A more detailed account is given in Ref. [21].

The total social cost (€ tC^{-1}), c_i, of releasing 1 tC contained in type i residues (through combustion) is composed of individual GHGs contributions, $c_{ij}(t)$. The contribution of each GHG (€ tC^{-1}) is

$$c_{ij}(t): = \rho_j p_j(t)\lambda_{ij} - \rho_j \int_0^\infty e^{-rs} p_j(t+s)\phi_{ij}(t,s)m_i(t,s)ds, \tag{A.1}$$

and, hence, the total cost is

$$c_i(t): = \sum_j c_{ij}(t) = \sum_j \rho_j p_j(t)\left[\lambda_{ij} - \int_0^\infty e^{-rs}\frac{p_j(t+s)}{p_j(t)}\phi_{ij}(t,s)m_i(t,s)ds\right]. \tag{A.2}$$

We define the "carbon equivalent REF", $\varepsilon_i^{eq}(t)$, through the equation

$$\varepsilon_i^{eq}(t): = \frac{c_i(t)}{\rho_{CO2}p_{CO2}(t)}, \tag{A.3}$$

which implies that

$$\varepsilon_i^{eq}(t) = \sum_j \frac{\rho_j}{\rho_{CO2}}\frac{p_j(t)}{p_{CO2}(t)}\left[\lambda_{ij} - \int_0^\infty e^{-rs}\frac{p_j(t+s)}{p_j(t)}\phi_{ij}(t,s)m_i(t,s)ds\right]. \tag{A.4}$$

If CO_2 is the only gas that is emitted (i.e. $\lambda_{i,CO_2} = 1$ and $\phi_{i,CO_2}(t,s) = 1.$), Equation (A.4) reduces to Equation (5). As in the CO_2-only case, the "carbon equivalent EEF" ($gCO_2eqv.\ MJ^{-1}$) is

$$\hat{\varepsilon}_i^{eq}(t): = \eta_i^{-1}\kappa_i\rho_{CO2}\varepsilon_i^{eq}(t). \tag{A.5}$$

The carbon equivalent REF and EEF can be used to emission taxes for residue combustion in the same way as in Section 4.3, i.e. $\tau_i = \varepsilon_i^{eq}(t)p(t)$ and $\hat{\tau}_i = \hat{\varepsilon}_i(t)\,p(t)$.

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